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Exploiting solar energy potential through thermal energy storage in Slovenia and Turkey

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A B S T R A C T

Thermal energy storage (TES) is regarded as among the most feasible environmentally friendly solutions for saving energy. R&D activities for heating and cooling of buildings lead to the development of various technology types.

This paper attempts to give an overview of the energy situation, solar energy potential, TES concepts and technologies used in solar applications around the world with the emphasis on two Mediterranean countries, Turkey and Slovenia. Energy savings and CO_2 emission reduction potential when TES is used in various solar applications of buildings are also discussed.

Contents

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1. Introduction

The foremost global challenges facing the energy market today are growing environmental concerns, especially climate change, economic development and energy security. Developing and deploying more efficient and less environmentally damaging energy technology is critical to achieve objectives of energy security, environmental protection and economic and social development. It is not fully clear what would be the world population and energy demand at the end of the present century, but it is also obvious that searching for new energy sources is required because of diminishing gas and oil supplies. The increasing interdependence of energy markets requires new approaches to energy technologies and policies.

Solar energy is the most important renewable energy source that waits to be exploited to meet the global challenges of the energy market. Besides biomass and hydropower, solar thermal is the second largest renewable energy source following wind power in meeting global energy demand. According to Solar Heat Worldwide Report [1], by the end of 2010, installed capacity was 195.8 GWth corresponding to 279.7 million m^2 of collector area in operation in 55 countries representing more than 90% of the solar market in the world. The calculated number of different types of solar thermal systems in operation exceeded 53 million by the end of 2010. Hereof, an estimated 85% were used for domestic hot water preparation in single family houses and 10% were attached to larger domestic hot water consumers such as multifamily houses, hotels, hospitals, schools, homes for elderly people, etc. The remaining 5% of the worldwide installed capacity supplied heat for both domestic hot water and space heating (solar combisystems) and for other applications, such as solar supported district heating, industrial processes and solar air conditioning applications.

Solar energy with its intermittent characteristics needs to be stored for efficient utilization. Thermal energy storage technologies are used to close the gap between supply and demand of such intermittent resources. Duration of the storage can be short and diurnal, respectively (day/night) or long and seasonal, respectively (summer/winter). For seasonal storage (summer/winter), underground thermal energy storage (UTES) is one of the mostly used in solar plants. For short term applications thermal energy storage in water or rocks, phase change materials (PCM) and thermo-chemical reactions are preferred. Recently there are hybrid systems that combine short and long term storage technologies in the same system.

Global energy security concerns and environmental policy issues are assuming more important roles as driving forces in energy technology progress and encouraging greater international collaboration. Turkey and Slovenia are cooperating on the three years joint project with the title: Thermal Energy Storage for Efficient Utilization of Solar energy. This article gives the overall situation in energy, solar energy, TES concepts and applications as well as energy savings potential in the mentioned countries.

2. Current energy situation

2.1. Slovenia

Energy use in Slovenia has been increasing in the past decades and is based on solid fuels, nuclear energy and renewable energy sources. Slovenia, as a member of the European Union, had to adopt all European guidelines and directives on energy especially for the promotion of renewable energy sources.

Energy use is followed statistically by the Office of Energetics governed by the Ministry of Economy [2]. Use of primary energy was 273.7 PJ in 1997 and the sources were: oil products (104.3 PJ), nuclear energy (67.7 PJ), coal (58.7 PJ), natural gas, hydro energy and renewable sources. Consumption of primary energy was 308.2 PJ in 2011. In the last fifteen years energy consumption increased for 34.5 PJ, which represents 12.6% increase. Data can be seen in Fig. 1. Consumption of final energy was 206.6 PJ in 2011. Oil products represented the largest share (103.4 PJ), followed by electricity (46.0 PJ), natural gas (29.0 PJ), renewable sources (15.7 PJ) and others.

Final energy consumption is divided into three major groups: traffic, industry and households. In traffic oil products (75.7 PJ), in industry natural gas (22.7 PJ) and electricity (20.8 PJ), in households electricity (24.3 PJ), oil products (21.0 PJ) and renewable sources of energy (13.4 PJ) prevail (Fig. 2). Largest share of renewable sources is being used for households, oil products for traffic, electricity has large share within industry as well as in households.

2.2. Turkey

Turkey is one of the rapid developing countries in the world. In 2010, Turkey was the 16th largest economy in the world and the 6th largest economy in Europe [3]. Recently Turkey had a

Nomenclature

a	fraction/solar collector area per building, m^2/building
B	building stock
c_p	specific heat capacity, kJ/kgK
E	energy saving, GWh$_{th}$
f	weighted CO_2 emissions conversion factor, g $_{CO2}$/kWh$_{th}$
H	heating capacity of district heating system
Δh	heat of (fusion, reaction), kJ/kg
I	implementation percentage
L	load reduction
lr	expected/estimated load reduction per building, kW$_{th}$/building
m	mass, kg
n	new buildings yearly construction completion percentage
R	greenhouse gas emissions reduction, kg
r	buildings yearly renovation percentage
s	specific solar gains, kWh$_{th}$/m^2
T	temperature, °C, K
t	time, s, number of years of the considered scenario
V	volume, m^3
$\%lr$	load reduction estimation
y	yearly operating hours

Greek letters

ρ	density, kg/m^3

Subscripts and superscripts

ap	average between T_i and T_f
e	electrical
f	final, fusion
i	initial
lp	average between T_m and T_f
m	melting, melted
pcm	phase change material
r	reaction, reacted
sp	average between T_i and T_m
$stge$	storage associated value

Acronyms

ATES	aquifer thermal energy storage
COP	coefficient of performance
EEU	energy efficient use
EU	European Union
GSHP	ground source heat pump
HTF	heat transfer fluid
NEP	national energy plan
NREAP	national renewable energy action plan
PCM	phase change material
PV	photovoltaic
RER	renewable energy resource
RES	renewable energy source
R&D	research and development
SDHW	solar domestic hot water
SDHW&H	solar domestic hot water and heating systems
SGCHPS	solar ground coupled heat pump system
SHS	sensible heat storage
TES	thermal energy storage

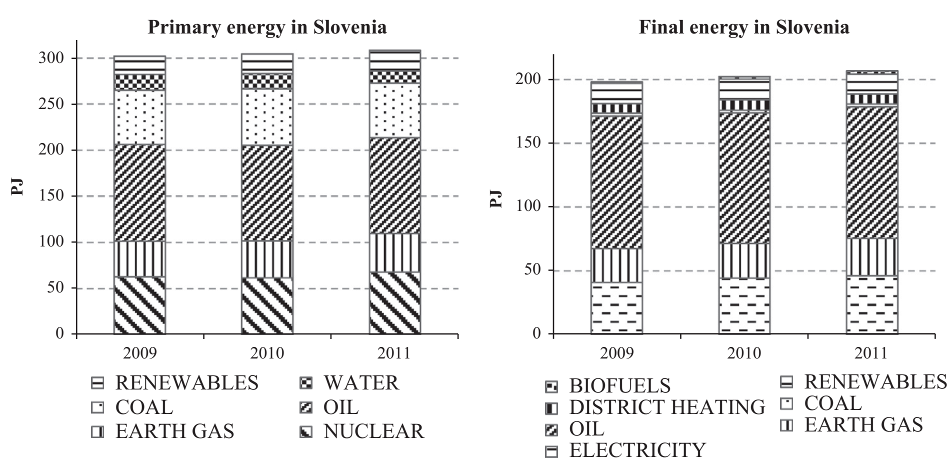


Fig. 1. Energy in Slovenia: primary energy (left) and final energy (right).

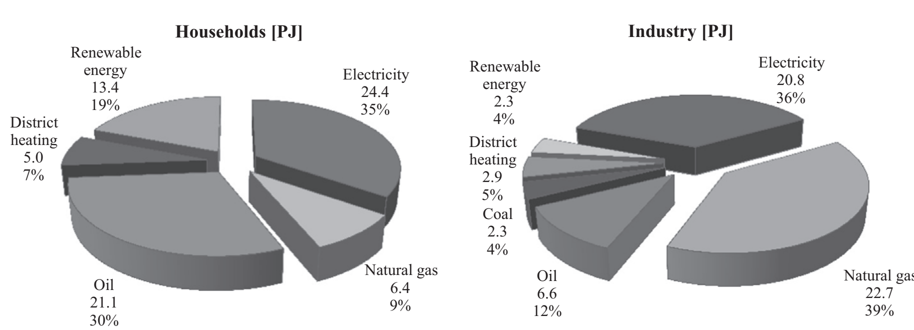


Fig. 2. Final energy in Slovenia (PJ) for year 2011: in households (left) and in industry (right).

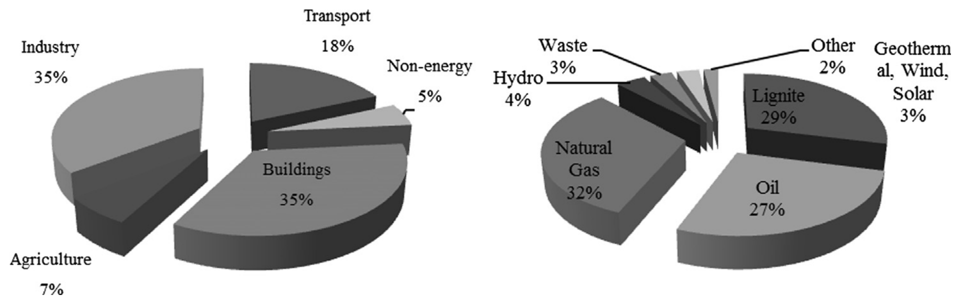


Fig. 3. Breakdown of primary energy consumption in Turkey: according to sectors (left), according to sources (right) [5].

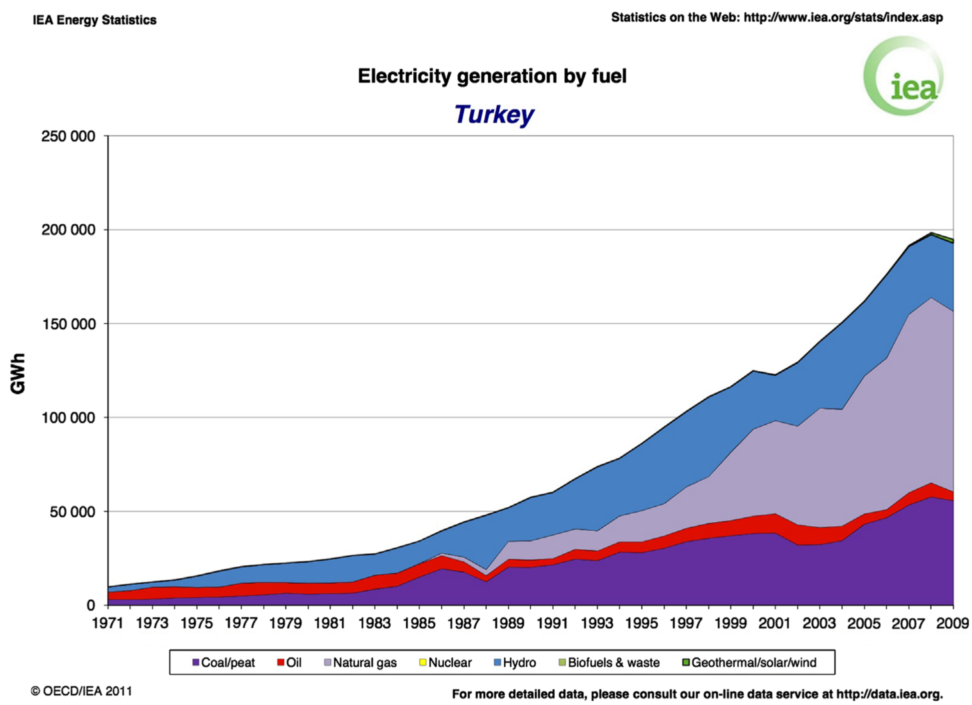


Fig. 4. Electricity generation of Turkey by fuel sources [8].

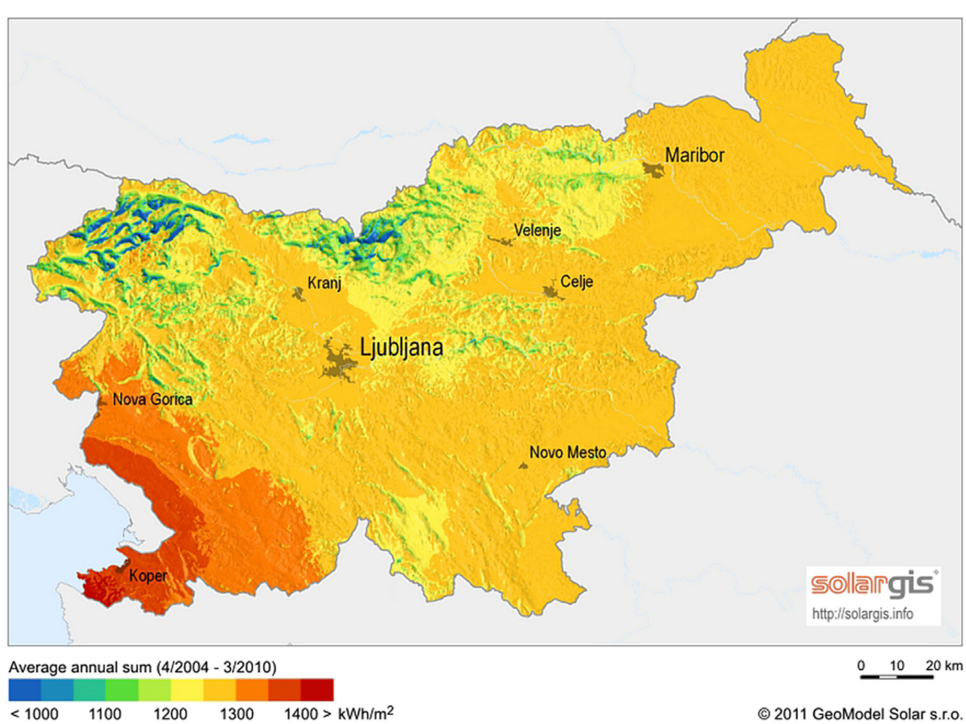


Fig. 5. Average annual global horizontal irradiation in Slovenia [10].

population of 71.9 million with 1.8% growth rate. Annual income was approximately 9000 USD/capita in 2011, which is 3 times as much as in 2000. Additionally, due to population increase, economic and industrial development, energy consumption also rises every year. Industrial energy consumption showed nearly 6 times increase in 35 years and also residential energy consumption has increased 3 times in the last 35 years. In 2011, Turkey's primary energy supply and total final consumption were 114.5 Mtoe (4794.0 PJ) and 86.9 Mtoe (3868.4 PJ) [4].

Fig. 3(left) shows that industry and buildings are leaders in primary energy cosumption with a share of 35% each, followed by transportation. 85% of the primary energy demand is met through fossil fuels (Fig. 3right). Fig. 4 indicates electricity generation by fuel resources. As one can see from Fig. 4, natural gas share has significantly increased in electricity production in recent years. In accordance with the increasing natural gas consumption, hydro power share in total electricity production has reduced to about 20% in the last 10 years. This also brings several bottlenecks of economics, energy security, diversity, stability and environmental factors [6]. As an impressive example of economic burden; Turkey had to import 77% of fossil fuel for its demands in 2009 [7].

Main supplies of renewable energy in Turkey are hydropower and biomass, but air pollution and deforestation concerns have led to a decline in biomass use, mainly for residential heating. Total renewable energy supply declined from 1990 to 2009, due to a decrease in biomass supply [7]. As a result, the shares of renewable energy supply have changed and wind power is beginning to claim market share.

3. Solar energy potential

3.1. Slovenia

Measurements of environmental data have been carried out for many years. Among other measurements, solar irradiation (Fig. 5) is one of the most predominant. Data are given in the book *Solar radiation in Slovenia* [9]. From the results we can conclude that solar radiation is non-uniform throughout the year. The use of solar energy is therefore closely connected to energy storage. Average day values are presented in the Table 1 for the towns: Ajdovscina, Brnik, Novo mesto, Koper, Maribor and Ljubljana.

Table 1
Data for average day solar irradiation in Slovenia.

Place	Average day solar irradiation (kWh/m^2-day)
Ajdovscina	3.21
Brnik	2.95
Novo Mesto	3.03
Koper	3.40
Maribor	3.01
Ljubljana	2.96

Theoretical potential of solar irradiation in Slovenia can be calculated in relation to the country's area as 26×10^{12} kWh/year [11]. The potential must be reduced since only one part of Slovenia can be covered with technological devices for solar energy conversion. Forests, fields, rivers and roads have to be excluded. Therefore the total potential of solar irradiation on horizontal area which can be used for heat and electricity conversion is 5.3×10^{12} kWh/year. Technical potential of solar radiation with consideration of all roofs on houses is 8.3×10^{10} kWh/year.

3.2. Turkey

Turkey, lying in the sunny belt between 36°N and 42°N latitude, is located in a relatively advantageous geographical location for solar energy. Fig. 6 shows mean annual solar irradiation distribution of Turkey. Especially, Mediterranean and Aegean Sea coasts have very high potential for utilization of solar energy.

Turkey's average annual total sunshine duration is calculated as 2640 h (daily total is 7.2 h), and average total irradiation as 1311 kWh/m^2-year (daily total is 3.6 kWh/m^2). Solar energy potential is calculated as 380×10^{12} kWh/year (See Table 2). Table 2 presents monthly solar energy rate and sunshine duration. Regarding solar radiation potential in 25 EU member and 5 candidate countries, Turkey takes place in the top five [13].

Table 2
Monthly average solar potential of Turkey [12].

Month	Monthly total solar energy (kWh/m^2-month)	Sunshine duration (h/month)
January	51.75	103
February	63.27	115
March	96.65	165
April	122.23	197
May	153.86	273
June	168.75	325
July	175.38	365
August	158.40	343
September	123.28	280
October	89.90	214
November	60.82	157
December	46.87	103
Total	1.311	2.640
Average	**3.6 kWh/m^2**	**7.2 h/day**

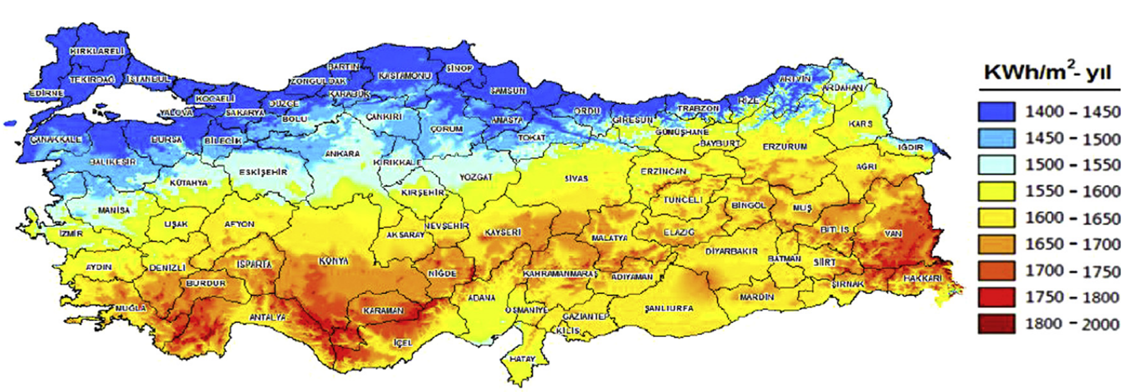


Fig. 6. Mean annual solar irradiation distribution of Turkey [12].

4. TES systems used and solar applications

In the following section only existent applications or systems in Slovenia and Turkey are presented. For a general knowledge on TES reader can refer to Appendix, where TES concepts are presented and TES technologies in solar applications with relevant references.

4.1. Slovenia

In the next pages some examples of solar energy use in Slovenia are presented. Most of them are collected in the frame of EU funded project SOLARGE [14].

In 2001 Hotel Delfin, Izola was renovated (Fig. 7). Roof which was sloped before is now flat and supports solar collectors which are designed exclusively for heating of salt water for internal and external swimming pools. The heat storage has integrated tube heat exchangers which are connected to the pool, where fresh sea water is added and disinfected. Storage volume is 15 m^3.

Elderly home Preddvor (Fig. 8) is home of 190 people. There are two residential buildings, an older one (1860) and a newer one, built in 1990. The buildings are well maintained, still not thermally insulated. Since 2003 the buildings are heated by biomass district heating plant. Storage volume is 8.4 m^3.

A solar system was built for hotel Zusterna at the seaside (Fig. 9). It is used for heating of the outdoor swimming pool and was installed during the renovation in 2001. The whole roof of indoor swimming pool is used as a solar roof with unglazed solar collectors. The cost of the solar collector was only 40.2 €/m^2



Fig. 7. Photos of solar system in Izola.

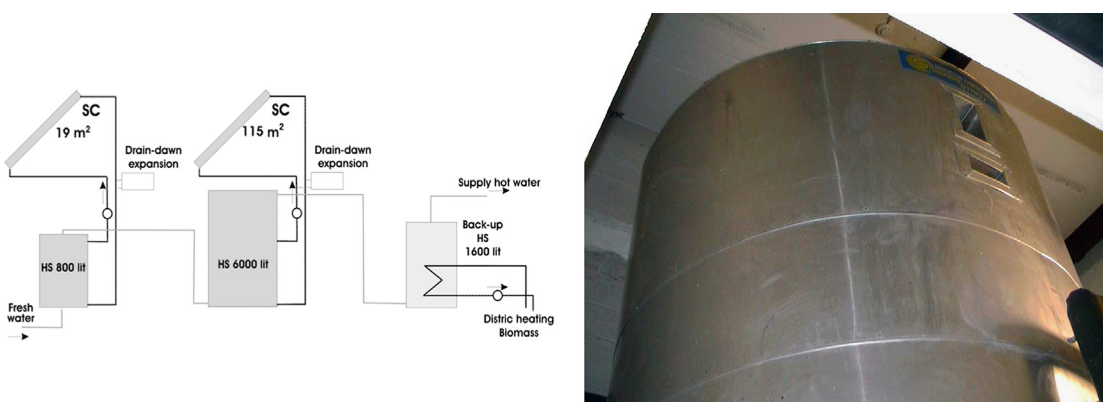


Fig. 8. Scheme of a system in Preddvor (left). Photos of storage tank in Preddvor (right).



Fig. 9. Scheme of a system in Zusterna (left). Photos of solar system in Zusterna (right).

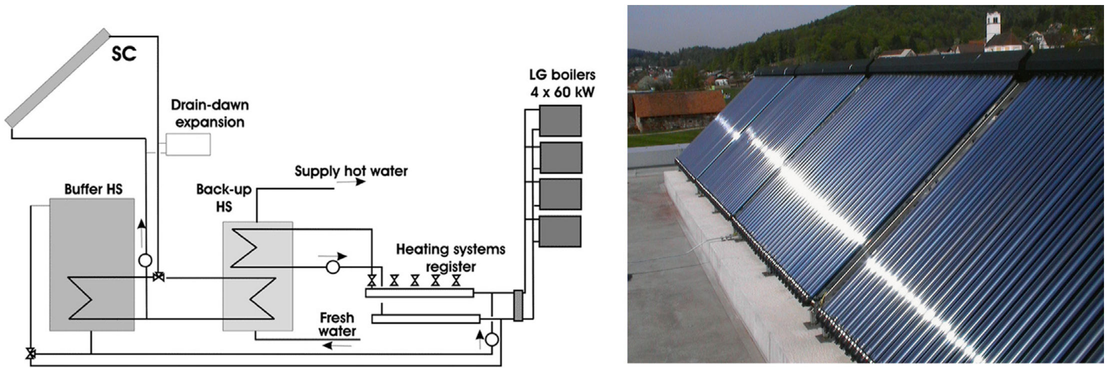


Fig. 10. Scheme of a system in Brezovica (left). Photos of solar system in Brezovica (right).

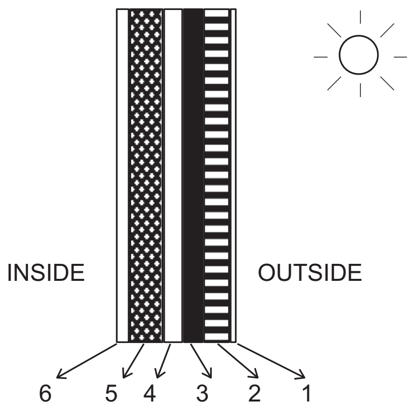


Fig. 11. Elements of PCM solar wall [16].

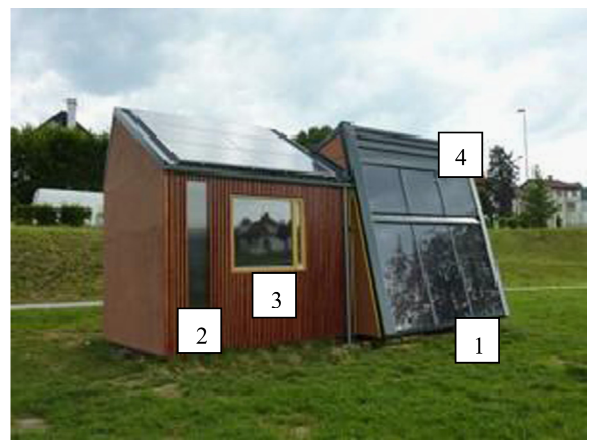


Fig. 12. Self sufficient residential unit [17].

because only additional costs for stainless steel piping and pump had to be paid. Storage volume is 2 m^3.

Technology centre Span d.o.o., Brezovica pri Ljubljani consists of several low-energy buildings. They use only vehicles run by LPG or electricity and recycle 75% of all waste fluids from the carwash. For domestic hot water, floor heating and heating of industrial water a solar system with vacuum collectors was built. As can be seen from Fig. 10(left), there is a buffer heat storage and back-up heat storage, their size is 2.5 m^3 altogether.

For the cogeneration of heat and electricity thermo-power plant Ljubljana (TE-TOL) is using coal and wood biomass technology in three major units: unit 1, 2 and 3. Boilers of units 1 and 3 are connected to two condensing turbines, boiler of the unit 2 is connected with a back-pressure turbine to two regulated steam extractions. When all the heat is not delivered to the users, it is stored in the storage with dimensions: 30 m in diameter and 50 m in height [15].

A facade construction designed for storage of heat from solar radiation falling on the absorber plate with PCM was developed in the Laboratory for Heating, Sanitary and Solar Technology at the Faculty of Mechanical Engineering in Ljubljana [16]. The wall consists of six main components (Fig. 11). The wall construction operates on the following principle: short-wave solar radiation passes through glass with TIM (Transparent Insulation Material) (1, 2) which at the same time prevents convective and short-wave radiation heat transfer. Black paraffin wax (3) in a transparent plastic casing made of polycarbonate absorbs and stores energy. The air for the house ventilation is heated in the air channel (4) and is led into the room. Insulation (5) and plaster (6) are standard elements in the room.

In the frame of IDES-EDU project self-sufficient residential unit was built [17] (Fig. 12). The basic heating system of the unit is solar hot water system with flat solar collectors (1), which are a source for heat for floor and wall heating units and radiator heating of sanitary unit. Housing unit is reheated with a hot air heater (2), which is part of the ventilation system of this unit. Housing unit is heated also with 'solar radiator' (3), a mobile thermal storage unit in which heat is stored in PCM. Sanitary unit will heat up also with hot air vacuum solar collectors (4).



Fig. 13. Thermal storage system in Vransko [18].

Near factory Kiv in Vransko a district heating system is installed which operates on wood biomass [18]. In addition 890 m^2 solar collectors are installed from autumn 2011 on the roof of the production hall in order to cover the need of DHW for the entire village. They replaced oil heating boiler, as well as contribute to a

more efficient use of biomass. A thermal storage system of 100 m^3 is mounted near the factory to store hot water for night time (Fig. 13). System is expected to produce 400 MWh of heat annually and the estimated reduction in CO_2 emissions is 200 t per year.

Slovenia participated in EU project with the title: Increasing the Market Implementation of Solar Air-conditioning Systems for Small and Medium Applications in Residential and Commercial Buildings – SOLAIR [19]. The objectives of the project were to promote and disseminate activities of solar air-conditioning on the national level and Europe-wide. Almost all analyses were carried out for Slovenian hospitals and some of the data and calculated values are presented in Table 3. Comparing collector area with volume of thermal storage it was found that this ration varied from 13 to 23 m^2/m^3. In the conclusions it was stated that up to 90% of energy needs for cooling can be provided with solar air-conditioning. Studies also revealed that projects can be financially viable with the support of EU Cohesion Fund.

Concerning market applications it could be concluded that there are many companies dealing with heating, cooling, heat pumps and DHW. Most of them are listed on the website of Energy Restructuring Agency [20], which is one of the leading Slovenian independent consulting companies in the field of energy efficiency and renewable energy sources.

4.2. Turkey

Solar thermal applications apart from hot water systems that utilize flat plate collectors are at R&D stage in Turkey. The first solar house was built for experimental purposes back in 1971. Table 4 shows the solar houses in Turkey. It can be seen that the performance of these solar houses has been increasing with new systems. Thermal storage systems in the solar houses given in Table 4 all use sensible heat.

In the following passive solar project, thermal energy storage in microencapsulated phase change materials (PCMs) together with insulation materials was utilized to decrease heating and cooling load of a test cabin of 4 m^2 floor area in Adana, Turkey (Fig. 14 left). Two different PCMs – Micronal 5001 – BASF (melting point 26 °C and latent heat 110 kJ/kg) and Micronal 5008-BASF (melting point 23 °C and latent heat 110 kJ/kg)—were used. Macro-packages of PCM in rectangular shape (0.35×0.30 m^2) and thickness 0.05 m were prepared using aluminum foil. Total amount of PCM used was 3.5 kg. As insulation material Izopan–IZOCAM, which is a sandwich panel of glass wool in-between aluminum layers, was used. The energy conservation was 7% for cooling and 23% for heating as a result of using PCM macro-packages lined on the walls as shown in Fig. 14 (right) [21].

Experimental evaluation of seasonal latent heat storage was made in the heating system of a 180 m^2 greenhouse located in Turkey [22]. This system was composed of five main parts: flat plate solar air collectors, latent heat storage unit, experimental greenhouse, heat transfer unit and data acquisition system. The latent heat storage unit was a cylindrical steel tank, filled with 6000 kg of paraffin wax as a PCM. The system reached the average efficiency of 40%.

Another R&D project for a greenhouse heating and cooling does not use solar collectors, but uses greenhouse itself as the solar collector. Two separate greenhouses with polyethylene covers, each having an area of 360 m^2 for growing tomatoes at Cukurova University, Adana research farm have been used. The first

Table 3
Comparison of solar cooling parameters for Slovenian hospitals.

	Kranj	Postojna	Sezana	Izola	Valdoltra
Hospital area (m^2)	3878	2864	4705	19600	18250
Collector area (m^2)	80	151	262	805	503
Thermal (heat) storage (m^3)	6	8	20	35	35
Coefficient of performance COP (−)	0.7	0.7	0.7	0.7	0.7
Thermal (cold) storage (m^3)	1	1	1	5	5
Collector area/thermal storage (m^2/m^3)	13.3	18.9	13.1	23.0	14.4
Heat for solar cooling (kWh)	21073	17420	42100	87240	53040
Cold produced	14108	11820	27350	58500	35500
Heat/collector area (kwh/m^2)	681	681	808	735	805
Savings of electric energy (kWh)	5000	3800	8800	21200	11450
CO_2 emission reduction (t)	11.4	29.6	61.7	180	122
CO_2 emission reduction/hospital area (kg/m^2)	1900	3700	3085	5143	3486

Table 4
Solar houses in Turkey.

Solar house	Location, year of construction	Type	Thermal storage	Heat transfer fluid	Solar energy covering heating load (%)
MTA	Marmaris, 1971	Passive	Trombe wall	Air	30
MTA Chemistry Lab	Marmaris, 1981	Active	Gravel	Air	NA
Cukurova University	Adana, 1981	Passive	Greenhouse+Trombe wall	Air	NA
Ege University	Izmir, 1991	Passive	Greenhouse	Air	85
Ege University – Gama type	Izmir, 1990	Passive	Greenhouse+Trombe wall	Air	85
Hacettepe University	Ankara, 2003	Active+Passive	Gravel	Air	NA
METU	Ankara, 1980	Active+Passive	Water+Greenhouse	Water	22.4
Ankara Municipality	Ankara, 1993	Passive	Air	Air	73
TUBITAK guesthouse	Antalya, 1996	Passive	Greenhouse+Trombe wall	Air	NA
Erciyes University	Kayseri, 1996	Active	Water	Air	84.5
Erciyes University with floor heating	Kayseri, 1998	Active	Water	Water	86
Erciyes University Sports Hall	Kayseri, 2001	Active	Water	Air	73
Denizli PAU	Kayseri, 2007	Passive	Trombe wall+Water	Air+Water	NA
Diyarbakır	Diyarbakır, 2007	Passive	Greenhouse+Trombe wall	Air	NA

greenhouse has been heated and cooled by Aquifer Thermal Energy Storage (ATES) technology. The solar heat, accumulated in the greenhouse through the use of fan coils and perforated ducts shown in Fig. 15 (left), is injected into aquifer. By doing this greenhouse was cooled down in summer time. In the second control greenhouse a conventional heating system was used without any cooling. Two wells—a cold and a warm well—were operated for the ATES greenhouse. The wells had a depth of 80 m, casing diameter of 0.4 m and the distance between the wells was 100 m. The schematic diagram of the system is shown in Fig. 15 (right). The monitoring results show that 68% energy conservation and 40% increase in yield of products were realized. Apart from the electricity used for fans and pumps, "0" fossil fuel was consumed [23].

Esen [24] investigated a solar powered heat pump system which was connected to a cylindrical latent heat storage tank filled with 1090 kg calcium chloride hexahydrate ($CaCl_2 \cdot 6H_2O$) as a PCM. The experimental set-up (as seen in Fig. 16) was used to supply heat for floor heating with an area of 75 m^2 in a laboratory building in Turkey. When the sunshine was abundant and space



Fig. 14. Test cabin used (left). Microencapsulated PCM packages installed in the cabin (right) [21].

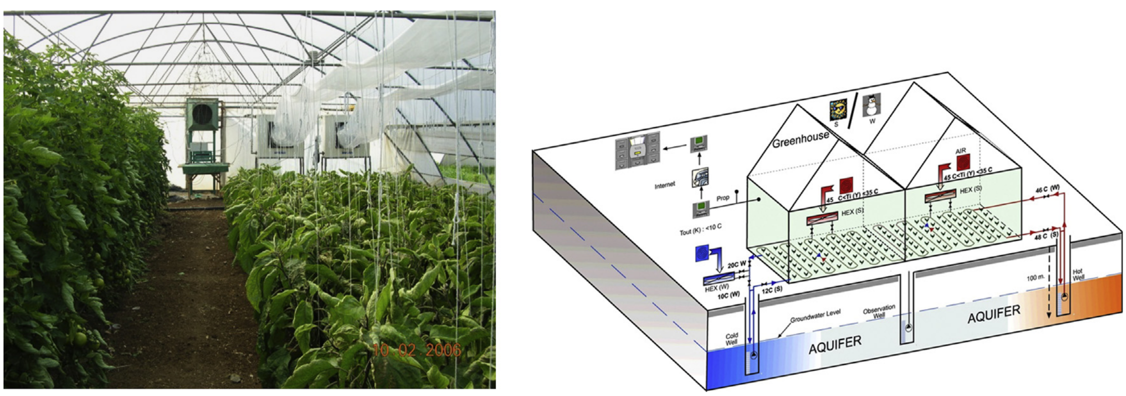


Fig. 15. Fan coils and ducts used for extracting solar heat from greenhouse (left). Aquifer thermal energy storage system used in greenhouse (right) [23].

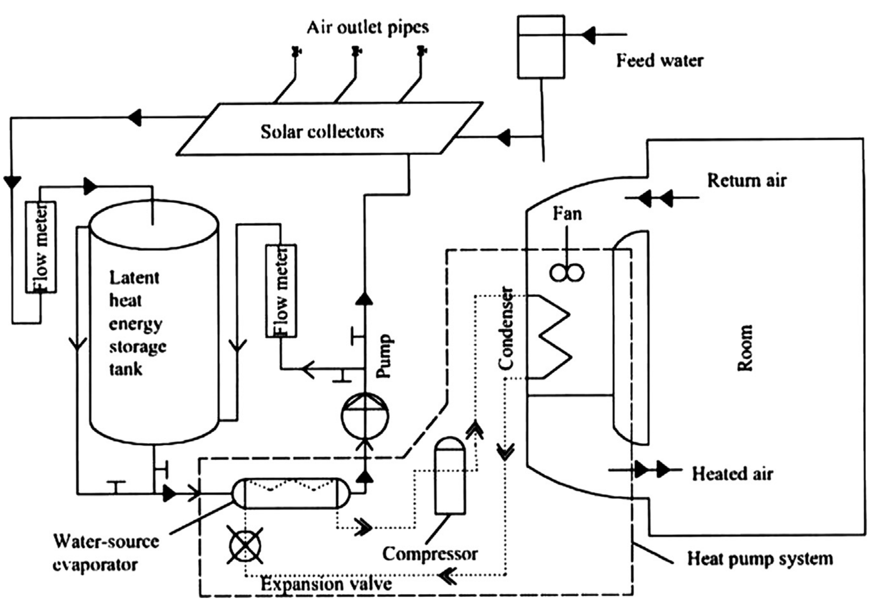


Fig. 16. Experimental set up for solar powered heat pump [24].

heating was required, the collected heat from solar collector was injected to the storage tank firstly and then used as a heat source for the water-source evaporator in the heat pump part. When the solar radiation was not available, the latent heat storage tank served as a heat supplier for the heat pump system. The ratio of E_{pcm}/Q (energy content of PCM/monthly total space heating load) was analyzed based on the experimental outcomes.

A project of ground-source heat pump heating system with a latent heat thermal storage tank, used for space heating in a 30 m^2 glass greenhouse, was investigated in Turkey as shown in Fig. 17 [25]. R-22 was chosen as a refrigerant cycling in the horizontal ground heat exchanger loop with a length of 246 m. 300 kg of calcium chloride hexahydrate was used as a PCM. Solar radiation and thermal energy from the heat pump provided heat to the indoor air and the PCM storage unit. According to the results obtained from October to May in heating seasons of 2005 and 2006, the COP of the ground-source heat pump varied from 2.3 to 3.8 and the combined COP of the whole system from 2 to 3.5. It was pointed out that PCM storage contributed to the rational heat distribution in the greenhouse due to its nearly constant phase changing temperature.

There are few commercial solar heating and cooling projects. In Southern Turkey, a solar cooling system of a hotel and resort complex in Sarigerme has been in operation since 2003. The system not only supplies solar cooling but also solar pool and space heating and solar-powered steam generation for the hotel laundry. Parabolic through collectors are used to collect the solar energy and the temperature is 180–250 °C [26].

The first low energy eco building for headquarters of the Industrial Park in Ankara (OSTIM) started operation in October 2009 (Fig. 18right). The system utilizes solar (both thermal and PV) and wind together with cogeneration and ground source heat pump [27]. Three different thermal storage systems are used. Ice storage is used for peak shaving. Borehole thermal energy storage is used as the heat sink of GSHP. Water tank is used as short term storage to supply hot water, space heating and heat to absorption chiller.

Status of the solar applications described in the previous chapter for Slovenia and Turkey is summarized in Table 5.

5. Installed capacity

5.1. Slovenia

In 2011, Slovenia had almost 189,000 m^2 of solar energy collectors, of which almost 170,000 m^2 were flat plate collectors and the rest were vacuum collectors [29]. At present only short-term thermal energy storage systems are being used in households for the domestic hot water and space heating. Currently there is no seasonal storage.

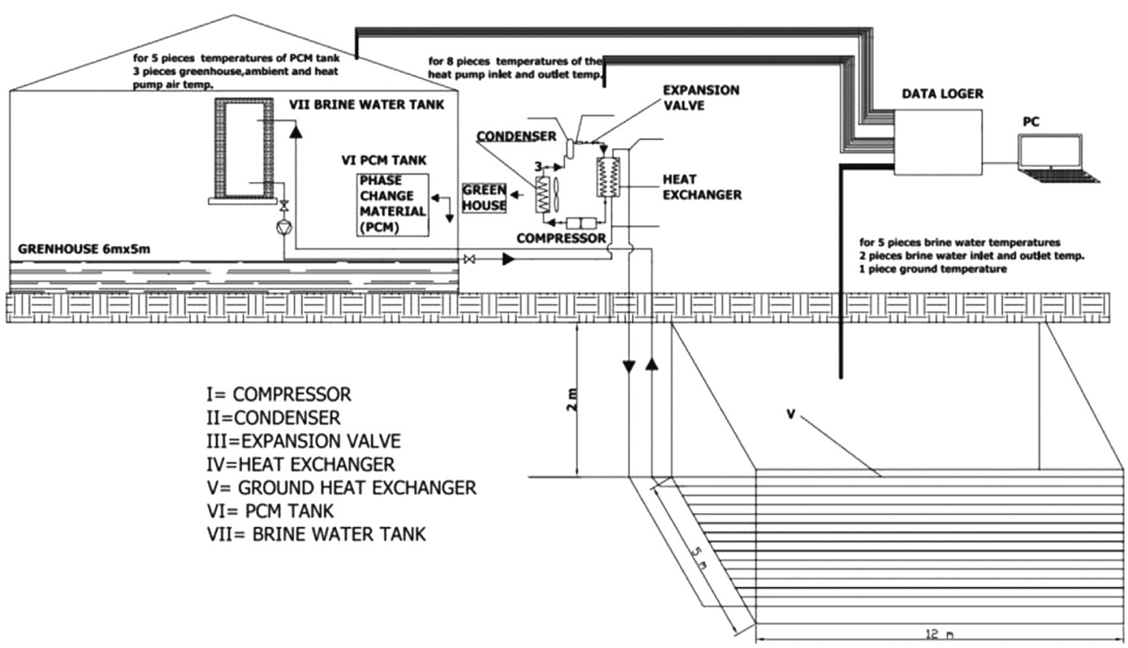


Fig. 17. Ground-source heat pump heating system with a latent heat thermal storage tank for greenhouse [25].



Fig. 18. OSTIM eco building concept picture [27].

Table 5
Current status and TES systems.

Application	Slovenia			Turkey		
	Research	Pilot	Market	Research	Pilot	Market
Heating/cooling (including heat pumps)	+[16,17]	+[14,17]	+[18,20]	+[24]	+[21,28]	+[27]
Domestic hot water	–	+[14]	+[20]	–	–	+[1]
Solar refrigeration – absorption/adsorption	+[19]	+[19]	–	–	–	+[26]
Solar thermal power plants	–	+[15]	–	–	–	–
Industry – air, water, steam	–	–	–	–	–	–
Agriculture – drying, greenhouses	–	–	–	+[22,25]	+[23]	–

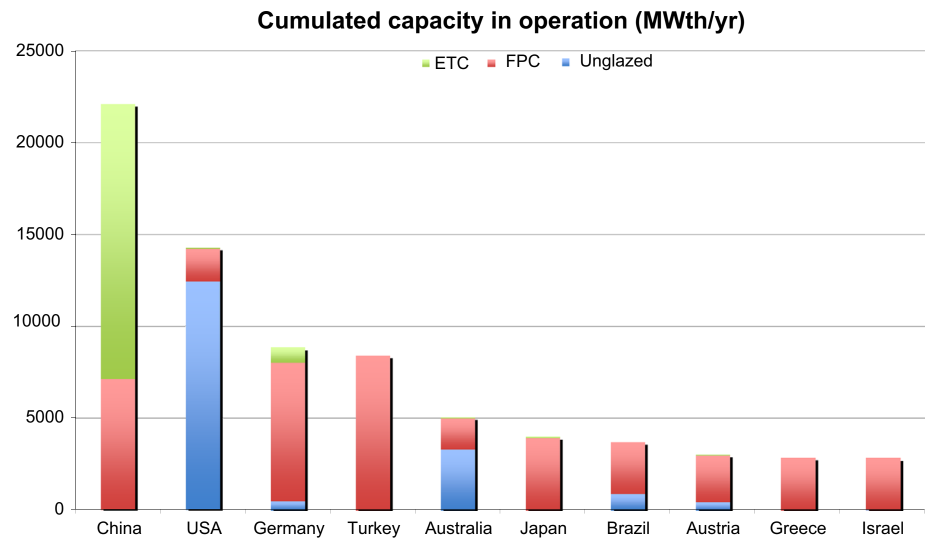


Fig. 19. Installed capacity of unglazed collectors in the world (FPC – flate plate collectors, etc – evacuated tube collectors) [31].

5.2. Turkey

Turkey is the fourth country (Fig. 19) in the world regarding total installed capacity of collectors. Altogether 13.3 million m² collector area is installed and these systems are mostly used in Aegean and Mediterranean regions. Total heat generation equals to 9323 MW_{th} with a corresponding CO_2 emissions reduction of 3.5 million tons/year [1]. The solar collector industry is well developed with high quality manufacturing and export capacity. The number of companies is around 100. Yearly growth in the solar thermal collector market is around 8% in the foreseeable future [30].

For solar power generation, two important developments took place in August 2011. The transformer centers to which solar power plants can be connected until 31 December 2013 were announced by Ministry of Energy and the License Regulation was amended. The installed capacity of individual solar power projects which will apply for license were capped at 50 MW with this amendment.

6. Legislations

6.1. Slovenia

As an EU country Slovenia had to take all the EU Directives into consideration where renewables must have a significant share. The most important renewable source of energy in the country is wood biomass, followed by hydro energy, while in recent years development has been most dynamic in exploiting solar energy and biogas [32]. Although the potential of solar energy is quite high, the utilization of this energy is still very low. Use of thermal energy storage technologies is the way to increase the share of solar energy in Slovenia even more.

The European Directive 2009/28/EC of 23rd of April 2009 on the promotion of energy from renewable sources dictates that each Member State has to adopt a national renewable energy action plan (NREAP) for the period 2010–2020. These plans must set out the national targets of Member States for the shares of gross final energy from renewable sources (hereinafter: RES) consumed in transport, electricity and heating and cooling for 2020. It was decided that Slovenia must achieve at least a 25% share of RES in gross final energy consumption by 2020.

In 2010 Slovenia adopted the NREAP [32] and its objective is to assess and determine the necessary quantitative values of energy consumption from RES by individual sector (heating and cooling, electricity and transport) and to propose measures to facilitate consumption of the desired quantity of energy from RES in future years. Besides that the effects of policies for efficient energy use (EEU) on final energy consumption need to be taken into account.

In the field of solar energy, the focus is mainly put on PV systems for electricity and solar panels for heating. There is a promotional scheme, which is implemented by the Eco Fund, the Slovenian public environmental fund. The authority supervising the scheme is – from 2010 on – the Ministry of the Economy. Support differs depending on the technology. The level of incentives amounts to 25% of acknowledged costs of investment but no more than 150 €/m^2 of surface of systems with panel collectors and no more than 200 €/m^2 surface of systems with vacuum collectors. National Energy Program (NEP) estimates that 669,000 m^2 of solar panels will be installed until 2020 and 1,557,000 m^2 until 2030. Purchase prices of electricity from solar

energy are guaranteed by the state for 15 years but the new regulation provides an annual reduction of prices. The current fid-in tariffs for solar energy produced in buildings (< 50 kWp) is 138.36 €/kWh [33]. From these figure the importance of heat storage is obvious. Moreover, it will be required also for solar cooling. On the contrary no concentrated solar power plants are foreseen in the NREAP, so no heat storage required.

6.2. Turkey

Turkey enacted its first renewable energy law in 2005 (Law No. 5346) and solar energy is considered within the context of this law. The aim of this law is to encourage the use of renewable energy resources (wind, solar, geothermal, biomass etc.) for the generation of electrical energy [34]. This law was a good start, but not sufficient. Recently, 8% of total electricity production comes from renewable energy sources in the EU. EU commission's target is to increase this share to 20% till 2020. In order to achieve this target, Turkish current renewable energy law had to be improved. Law No. 5346 has been amended in order to improve renewable energy incentives and boost renewable energy investment in Turkey and is in action now as of the end of 2010 [35]. The Amendment Law introduced the following incentives:

- *Feed-in tariffs*: The new tariffs for different renewable energy technologies are 7.3 $cents/kWh for hydropower and wind, 10.5 $cents/kWh for geothermal and 13.3 $cents/kWh for biomass (including landfill gas) and solar. The license holder can benefit from these tariffs for a period of ten years starting from its commissioning date.
- Additional incentives for domestically manufactured components, additional incentives for each domestic component used for a period of 5 years starting from their commissioning date will be given until 31st December 2015.
- Renewable Energy Resource (RER) support mechanism: This allows suppliers to be indirectly obliged to purchase electricity that is generated from renewable sources while they are allowed to reflect the cost of renewable generation to their customers' invoice.
- *Establishment of power plants in protected regions*: Renewable energy power plants can be built in environmentally sensitive areas with necessary permissions taken from authorities.
- *Reduced fees for land acquisition*: Same incentives provided by Energy Efficiency Law still apply but the scope of the incentive is expanded to renewable based plants commissioned before 31st December 2015.
- *Tax exemption*: Renewable based power plants are exempted from paying 1% treasury share.
- *Special provisions for solar power*: Total installed capacity of RER Certified solar power plants that can be connected to the transmission network until 31st December 2013 is limited to 600 MW. After that date, the Council of Ministers is authorized to determine total installed capacity of solar generators to be connected to the transmission grid.

Renewable energy law covers only power generation and does not include thermal use of solar energy. Building Energy Performance legislation that was brought in action based on Energy Efficiency Law (No 5627) in January 2011. According to this legislation all new and old buildings have to provide an energy identity document, which shows the classification of energy consumption and corresponding CO_2 emissions of heating and cooling system used. The buildings are obliged to have a classification of C or above. This legislation aims to enforce more renewable energy consumption in buildings [36].

7. Potential of TES in solar applications in Slovenia and Turkey

In order to calculate TES potential in solar applications for buildings, the methodology which can be found in [37] is used. In relation to energy three important parameters are determined:

- the derived thermal load reduction,
- thermal/electrical energy savings, and
- reduction of CO_2 emissions.

The potential thermal load reduction *L*, tells us how much does the capacity reduce when the energy storage is applied, assuming the same working conditions. The energy savings *E*, refer to the “heat” or “cold” that is stored and may be reutilized, thus not needing to be generated “again” by the application. The CO_2 emissions reduction R_{Co_2} is the one achieved as a result of reusing stored energy, therefore not consuming fossil fuels or other greenhouse gas emitting energy source during the energy conversion and thus preventing emissions from going into the atmosphere [37].

7.1. Methodology

Below are listed possible systems for buildings where TES can be used, their brief description and calculation procedure.

7.1.1. Seasonal solar thermal system

Seasonal solar thermal storage system store energy during the hot summer months and use it during colder winter weather. Solar thermal energy is captured by solar collectors and stored in different ways. The three above mentioned parameters used to calculate the TES potential are described with the following equations:

$$L = \{lrt(r+n)B\}I_{stge}/1000 \tag{1}$$

$$E = Ly/1000 \tag{2}$$

$$R_{CO_2} = (f/10^6)(10^6 E) \tag{3}$$

where *lr* presents expected/estimated load reduction per building, *t* number of years of the considered scenario, *r* buildings yearly renovation percentage, *n* new buildings yearly construction completion percentage, *B* building stock, I_{stge} implementation percentage of TES, *y* yearly operating hours, *f* weighted CO_2 emissions conversion factor.

7.1.2. District and central heating systems

District heating is a distribution network that transports heat generated in a centralized utility to residential and commercial buildings in city areas. The heat can be provided from a variety of sources. In this case load reduction can be calculated by the use of Eq. (4). Energy savings and CO_2 emissions reduction can be calculated by the same method used for seasonal solar thermal systems.

$$L = Ht \times \%lr/1000 \tag{4}$$

here, the parameters taken into consideration are: average heating load *H*, expected/estimated load reduction percentage that TES system is able to provide *%lr* and *t* number of years of the considered scenario.

7.1.3. Solar short term systems

For the calculation of TES potential reduction parameters the same methodology as in seasonal solar thermal case is used, but

with a slight modification

$$E = \{ats(r+n)B\} I_{stge}/10^6 \quad (5)$$

where a and s represent an area of solar collectors and specific solar gains, respectively.

7.1.4. Passive cold systems

Passive house is defined as a building in which a comfortable interior climate can be achieved and maintained without active heating or cooling systems. In this context PCMs are used as an adequate option. The reduction of energy consumption in this case means the reduction of CO_2, too. The three parameters are calculated in accordance with Eqs. (1)–(4) and adequate passive cold data. As a result of not using electrical air-conditioned equipment another parameter must be added: the electrical energy saving E_e, which is in this case calculated taking into consideration the energy savings E and the COP of the system.

$$E_e = E/COP \quad (6)$$

7.2. Results

For all above mentioned technologies calculations for 10 years span were carried out. Values of parameters used in the analysis are presented in Table 6. The TES potential reduction results for Slovenia, Turkey and EU-25 are presented below. For easier comparison of the results, data in the diagrams are given per person.

Fig. 20 presents TES potential results of load reduction and thermal energy savings. As seen from the results the most promising field for TES applications are district/central heating and solar short term systems. In colder countries like Slovenia district/central heating presents TES potential application. This can be a solution for achieving energy savings in cold climate countries. Solar short term systems present TES potential application in warm climate countries like Turkey for achieving energy savings. Seasonal solar thermal systems and passive cold systems are the least used technologies for TES application. In solar short term systems, Turkey has the highest thermal energy savings, 1.35 MWh/person. Regarding to district/central heating, Slovenia achieves the largest energy savings with 1.23 MWh/person. All savings are for period of 10 years.

Table 6
Parameters used in analysis of potential of TES in different solar systems for buildings including residential and non-residential

Parameters	Slovenia	Turkey
Seasonal solar thermal systems		
Estimated load reduction, *lr* (kW_{th}/building)	15	10
Building renovation rate per year, *r* (%)	1.82	0.2
New buildings constructed per year, *n*(%)	1.01	14
Building stock, *B*	1,161,966	17,070,093
Implementation percentage of TES, I_{stge} (%)	10	10
Operation hours per year, y (h)	1800	1800
Weighted CO_2 emissions conversion factor, *f* (g CO_2/kWh_{th})	258	300
District/central heating systems		
Heating load, *H* (GW_{th})	1.133	22
Estimated load reduction, *lr* (%)	20	20
Solar short term systems		
Estimated load reduction, *lr* (kW_{th}/building)	40	40
Solar collector area, *a* (m^2)	10	10
Solar gain, *s* (kWh_{th}/m^2)	400	750
Building renovation rate per year, *r* (%)	1.82	0.2
New buildings constructed per year, *n*(%)	1.01	14
Building stock, *B*	11,61,966	17,070,093
Implementation percentage of TES, I_{stge} (%)	20	80
Passive cold systems		
Estimated load reduction, lr (kW_{th}/building)	4.23	2
Implementation percentage of TES, I_{stge} (%)	3	3
COP	2.7	2.7
Weighted CO_2 emissions conversion factor, f (g CO_2/kWh_e)	530	850

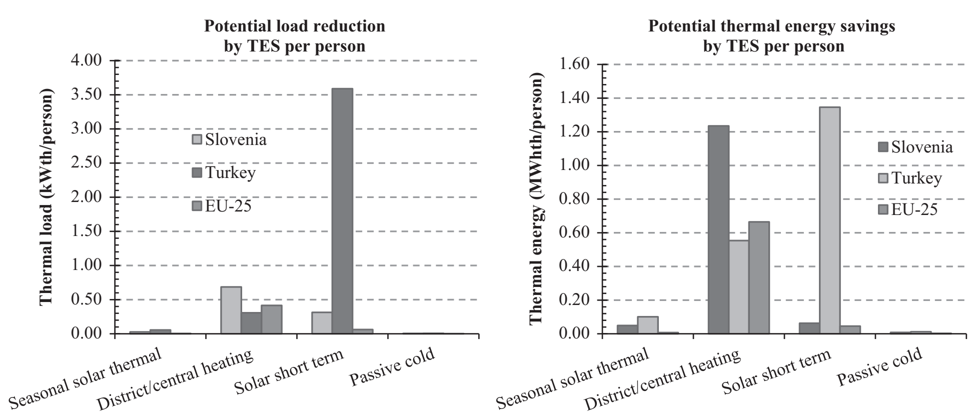


Fig. 20. Potential load reduction (left). Potential thermal energy savings (right).

As already mentioned, electrical energy consumption in buildings can be reduced by using the TES systems. Fig. 21 (left) shows an electrical savings of 3.2 GWh_e/person for Slovenia and 4.5 GWh_e/person for Turkey. The lowest value of electrical savings is 0.92 GWh_e/person for EU-25.

A great amount of CO_2 emissions could be reduced by use of solar short term systems and district/central heating systems. In solar short term systems Turkey could prevent release of 404 kg_{Co_2}/person to the atmosphere, followed by Slovenia with 16 kg_{Co_2}/person and EU-25 with 12 kg_{Co_2}/person. With district/central heating systems Slovenia could prevent release of 319 kg_{Co_2}/person to the atmosphere, followed by EU-25 with 180 kg_{Co_2}/person and Turkey with 166 kg_{Co_2}/person.

The results of this analysis confirm that based on climate conditions, for Turkey with high solar insolation hours, the short term solar potential is very high also. For Slovenia with a colder climate potential for district heating is higher. High passive cooling potential of Turkey can also be explained by a higher cooling demand based on climate.

8. Conclusions

For efficient utilization of solar energy, compact and cost-effective thermal storage systems with high energy storage density are essential. There is an urgent need to exploit the solar energy to meet the growing energy demand and to sustain the life on earth. Solar energy is abundant in Turkey and in Slovenia, but current applications are limited to solar domestic hot water utilization. R&D on other solar applications has been increasing in recent years.

Thermal energy storage potential calculated for different solar applications based on load reduction and energy savings show that the most promising field for TES applications for cold countries like Slovenia is district/central heating and for warm countries like Turkey is solar short term systems. Moreover, potential for electricity savings with TES is calculated as 3.2 GWhe/person for Slovenia and 4.5 GWhe/person for Turkey. The corresponding total CO2 emissions reduction potential for short term and district/central heating systems is 335 kg_{Co_2}/person for Slovenia and 570 kg_{Co_2}/person for Turkey. These results emphasize the significance of TES in solar applications. Solar applications with TES can be the major contributor to reach the ambitious CO2 emissions reductions set by EU.

Once solar systems are mass produced like conventional fossil energy systems and integrated into buildings, they will become competitive and will replace conventional systems. Current laws and legislations in Slovenia and Turkey supporting more use of renewables, but there is more to be done. A corrective pricing mechanism, such as a carbon tax, will also help competitiveness. More demonstration projects showing the benefits of solar applications with TES are needed.

Acknowledgments

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Appendix A: TES concepts

Thermal energy can be stored as a change in internal energy of a material as sensible heat, latent, thermo-chemical heat, or any combination of these. Fig. 22 gives a classification of materials used with these TES concepts, whereas comparison is given in Table 7.

A.1. Sensible heat storage

In Sensible Heat Storage (SHS), thermal energy is stored by raising the temperature of a solid or liquid. SHS systems utilize heat capacity and the change in temperature of the material during the process of charging and discharging. The amount of stored heat Q depends on the specific heat of the medium c_p, the temperature change and the amount of storage material. It is calculated as follows:

$$Q=\int_{T_i}^{T_f} V\rho c_p dT = V\rho c_p(T_f-T_i) \quad \text{(A.1)}$$

where: V is volume, ρ is density, T_i is initial temperature, and T_f is final temperature.

SHS has lower storage capacity than latent heat and thermo-chemical, therefore requires larger volume. This is the reason why an important criterion in selecting a material for SHS is ρc_p value. Another disadvantage is that energy is not stored or delivered at a constant temperature. A variety of substances have been used in such systems where water seems to be the best available liquid, because it is inexpensive and has high specific heat. Other liquids are organic liquids (heat transfer oils), certain inorganic molten salts, liquid metals, etc. Other possible form of substances is solid state. In this case rocks (for air heating applications), metals, ceramics etc. are being used.

A.2. Thermo-chemical heat storage

Thermal energy may also be stored as the energy of a chemical compound, and energy can be repeatedly stored and released in the same materials by reversible chemical reactions. This generally

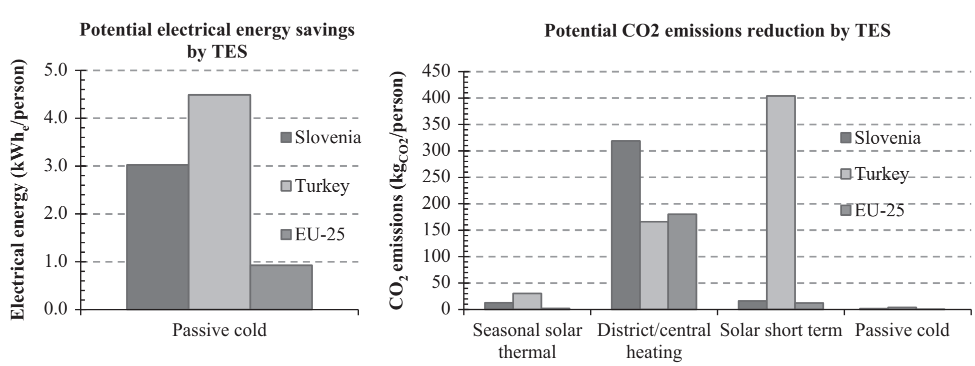


Fig. 21. Potential electrical energy savings (left). Potential CO_2 emissions reduction (right).

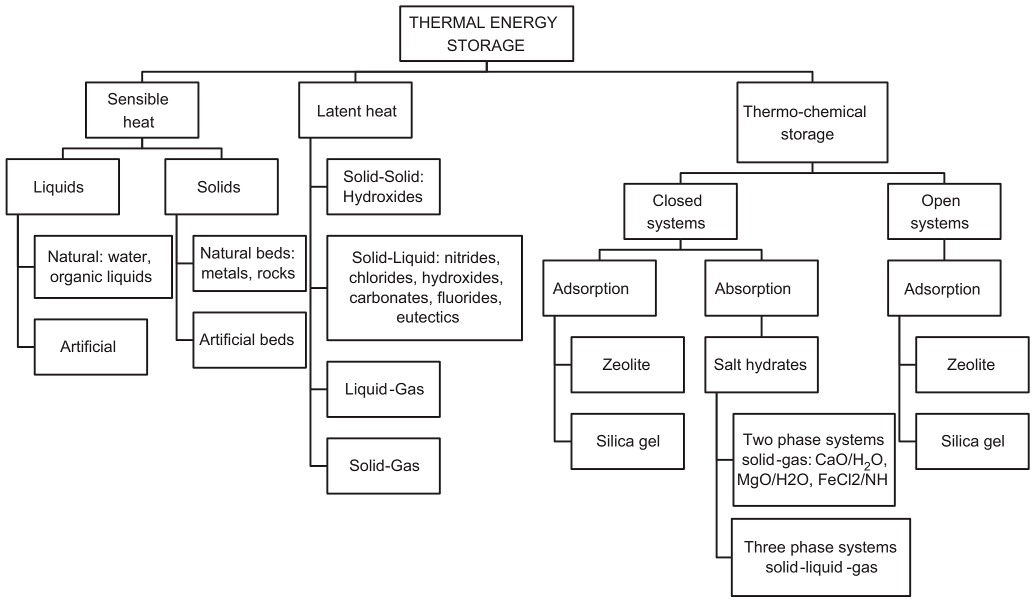


Fig. 22. Thermal energy storage technologies [38].

Table 7
Advantages and disadvantages of TES concepts.

	Advantages	**Disadvantages**
Sensible heat storage	Simple design	Size of the systems Not isothermal storage process
Latent heat storage	Isothermal storage process High storage density	Price Low thermal conductivity Almost no convection
Thermo-chemical storage	High energy density Cooling and heating possible (systems act as a heat pumps)	Complexity Expensive compounds Relatively high temperature required Limited experience with long-term operation

involves a reversible chemical reaction, absorption, adsorption or a hydration process. In principal, every chemical reaction can be reversed if it is carried out under suitably controlled conditions. Reactions absorb energy when proceeding in one direction and release it when proceeding in the reverse direction. The energy storage density of reversible chemical reactions is generally higher than the latent heat transitions. The amount of heat stored Q depends on the amount of storage material m, the heat of reaction Δh_r, and the extent of conversion a_r, as given in Eq. (A.2)

$$Q = a_r m \Delta h_r \tag{A.2}$$

The products can often be stored at ambient conditions (without thermal losses), for a long time and can often be transported easily. The storage density that can be achieved with these systems is the highest among other storage concepts. In spite of these advantages, thermo-chemical storage systems are not as common as sensible and latent storage due to difficult operating conditions [39].

A.3. Latent heat storage

Latent heat storage uses a phase change material (PCM) as a storage medium. PCM is a substance with high heat of fusion which is capable of storing and releasing large amounts of energy. The amount of stored heat equals

$$Q = m a_m \Delta h_m + \int_{T_i}^{T_m} m c_p d + \int_{T_m}^{T_f} m c_p dT$$
$$= m[a_m \Delta h_m + c_{sp}(T_m - T_i) + c_{lp}(T_f - T_m)] \tag{A.3}$$

where a_m is fraction melted, Δh_m heat of fusion, T_m melting temperature, c_{sp} average specific heat between T_i and T_m, c_{lp} average specific heat between T_m and T_f [40].

This can be accomplished through solid–liquid, liquid–gas, solid–gas and solid–solid phase transformations, but the only two of practical interest are the solid–liquid and solid–solid [40]. In solid–solid transitions, heat is stored when the material is transformed from one crystalline to another. This transition generally has smaller latent heat and volume changes than solid–liquid transition. Solid–liquid transformations have comparatively smaller latent heat than liquid–gas. However, these transformations involve only a small change in volume ($<$ 10%). Solid–liquid transition has proved to be economically attractive for use in thermal energy storage systems. For solar heating and for heat load levelling applications materials that melt between 15 °C and 90 °C can be applied.

PCMs have two important advantages as storage media: they can offer an order-of-magnitude increase in heat capacity, and for pure substances, their discharge is almost isothermal. For example, in the case of water, as much as 80 times of energy is required to melt 1 kg of ice as to raise the temperature of 1 kg of water by 18 °C.

A classification of PCMs is given in Fig. 23. They can be classified into the following major categories: inorganic compounds, organic compounds and eutectics of inorganic and/or organic compounds. Inorganic compounds include salt hydrates, metals and alloys, whereas organic compounds are comprised of paraffins, non-paraffins and polyalcohols Fig. 24.

Depending on the applications, PCMs should first be selected based on their melting temperature. Materials that melt below 15 °C are used for storing cold in various cooling applications, while materials that melt above 90 °C are used for absorption refrigeration, industrial and concentrated solar power applications. All other materials that melt between these two temperatures can be applied in solar heating and for heat load levelling applications. These materials represent the class of materials that has been studied most [41].

Appendix B: TES technologies in solar applications

Solar radiation is time dependent as it changes in cycles which suggests that it is necessary to store energy. Most solar systems use diurnal storage, however, weekly and seasonal storage is also used. At this point it is necessary to mention the two problems that arise when applying TES into solar energy systems. First one is size, as they need to be sufficiently large to permit the system to operate over periods of inadequate sunshine. Second one is a need of primary collecting system to be large enough to capture enough energy for periods of inadequate insolation [39].

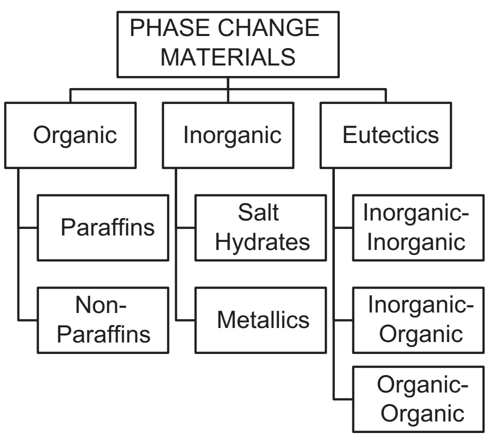


Fig. 23. Classification of PCM materials.

B.1. Solar water heating

Solar thermal energy can be directly used for hot water production from solar collectors of different types for different heat levels. At present the largest market of solar applications present residential buildings [42], where systems can be classified into three groups

- solar domestic hot water (SDHW) systems,
- solar domestic hot water and heating (SDHW&H) systems,
- swimming pools.

Water storage uses the sensible heat capacity of water (4.184 kJ/kgK) to store heat. Storage volume depends on the temperature difference between the water supplied from storage and return water. Water tanks are used in SDHW systems which use solar heat only for the hot water load. Stratified water storage is generally the simplest, most efficient, and cost-effective method. Stratification in the water storage tanks is based on the density difference of water to form horizontal layers or temperature zones based on its density. Hot water is naturally above the layers of cold water. Stratification allows optimal use of storage unit with limited heat losses. There are different methods for enhancing stratification like using diffusers of different designs [43] and adding PCM to water tank [44].

Solar combisystems are also known as solar domestic hot water and heating (SDHW&H) systems which use solar heat for both hot water and space heating demand. There are two different heat loads to supply using two separate heat sources, solar collectors and an auxiliary heat supplier. In these systems water storage is normally the central part of the system, and heat is usually stored from both the solar collectors and the auxiliary heater. Heat is supplied from the storage unit. In order to accomplish this, the storage generally requires heat exchangers for solar collector loop and for preparation of hot water, although immersed tanks or separate tanks can be used as well. Due to many options available, many different solutions have been developed and marketed [45].

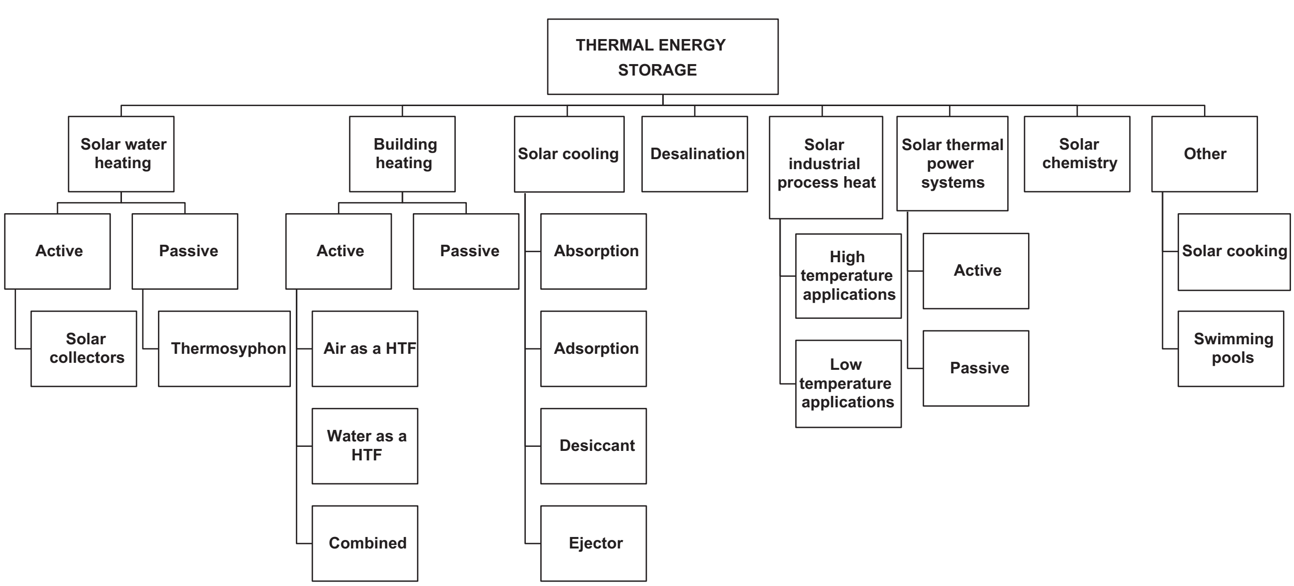


Fig. 24. Classifications of solar TES applications.

B.2. Building heating

B.2.1. Active building heating

Same principle which was mentioned in previous section can be used to provide heat for comfort in buildings diurnally, but in this case also systems with air as heat transfer fluid (HTF) are quite common. For seasonal storage systems significantly larger storage volume is necessary, especially for applications such as district heating network.

Systems with air as a HTF. Thermal energy is stored in a packed bed (pebble bed, rock bed, rock pile) by forcing heated air into the bed and utilized again by recirculating ambient air into the heated bed [46,47]. The amount of stored heat depends, apart from the thermophysical properties of the material, on the rock size and shape, packing density, HTF etc. This value is around 36 kJ/kg or 105 kJ/m^3 for a temperature change of 50 °C [46]. Another possibility is heat storage in phase change material (PCM), which is encapsulated in containers of different shapes [48].

Systems with water as a HTF. In case of water there is a great variety of storage possibilities. As mentioned above, heat absorbed in solar collectors can be stored in smaller water tanks within the building [49] as well as in tanks filled with PCM [50–52]. These two options are primarily meant for the diurnal storage. For seasonal storage boreholes [53], aquifers [54], underground water tanks or pits [55] and tanks filled with sand [56] are mainly used. There are also some studies with PCM storage tanks [57] and a review of seasonal storage can be found in [58].

Combined systems. Seasonal TES is also needed in solar ground coupled heat pump systems (SGCHPS) where solar energy is stored in storage medium (water) and used by the heat pump in the winter season [59,60]. Due to the implementation of TES evaporator temperature increases, collector operating temperature decreases and therefore, need for high performance collectors is reduced. Moreover, values of COP are better for SGCHPS.

B.2.2. Passive building heating

Building elements (windows, walls, floors, roof) and materials (concrete, plaster, wallboard) are used as storage media used in a passive heating. PCM addition to these building structures can enhance thermal mass and decrease heating/cooling loads. PCMs are installed in various locations in the building structure to store cold from night time and use it for cooling during daytime or vice versa. In such a way load can be reduced or shifted.

B.3. Solar cooling

Solar energy can also be used for cooling and there are four different available technologies: absorption, adsorption, desiccant and ejector cooling. The principle of operation is among others described in [61], here we will restrict ourselves to energy storage. Virtually in all four cases, energy is stored in the form of hot or cold water, but there are also some studies using PCM, where TES tank is placed between the solar collectors and the cooling machine [62] or after cooling machine [63]. In connection with absorption cooling hot water tank is used in [64,65], whereas in [66] both hot and cold storage are used. The same holds for adsorption, where hot water tank [67] or hot and cold water tanks [68] are used. With desiccant cooling also possibility of energy storage in salt solution opens up if we are talking about liquid desiccant. When solar energy is available the dilute solution is regenerated to its original concentration in a regenerator. The solution mainly used is lithium chloride[69,70], although there are also versions with two solutions (calcium chloride, lithium bromide) [71]. To such a systems a hot water tank can be added [72,73] which improves the performance of the system [74].

B.4. Desalination

TES is also important in applications which use solar energy to produce potable water. The most common examples of this are the solar ponds, however, also PCM was introduced. It was placed beneath the absorber plate to keep the operating temperature still high enough to produce distilled water during the lack of sunshine, particularly at night [75].

A solar pond is an artificial pool of saltwater which acts as a large-scale solar thermal energy collector with integral heat storage for supplying low temperature thermal energy (50–95 °C). Saltwater naturally forms a vertical salinity gradient, where the highest concentration is in the bottom layer and thus called the storage zone [76]. Heat can then be used in the multiple-effect distillation, multi-stage flash process or for a simple process where water evaporates from the pond is condensed and captured for drinking [76].

B.5. Solar industrial process heat

Systems which are designed for small contributions by solar in relation to the total loads can be operated without energy storage [61]. This applies to cases where the heat demand is always greater than the maximum output of the collector, which means no heat will be rejected. On the other hand it can happen that the operation of collectors is adapted to the industrial process, making it necessary to introduce TES. A review on solar energy use in industries can be found in [77] and the potential for renewable energy in industrial applications in [78].

B.5.1. High temperature applications

In applications with temperatures higher than 400 °C water cannot be used as a storage medium. Other storage media such as concrete [79], PCMs, pressurized water [80] and thermal oils [81] are used.

B.5.2. Low temperature applications

At lower temperatures (below 100 °C) which are required in food processing, textile industry, drying [82], greenhouses, etc. heat can be stored in the same way as in buildings (hot water, solid materials, PCMs) but it can be stored also in solar ponds. Latter ones are even appropriate for sodium sulfate production [83].

B.6. Solar thermal power systems

Storage concepts can be classified as active or passive systems. In active storage the storage medium itself circulates through a solar receiver. The main characteristic of a passive system is that heat transfers medium passes through storage only for charging and discharging. The heat storage medium itself does not circulate [84]. Appropriate storage media are presented in Table 8 and more information on solar thermal power plants is given in [85,86].

B.6.1. Active systems

Active thermal systems typically utilize tank storage and can be designed as one or two tank systems. A two-tank system uses one tank for cold HTF coming from the steam generator and one tank for the hot HTF coming directly from the solar receiver before it is fed into the steam generator. The advantage of this system is that cold and hot HTF are stored separately. The main disadvantage is the need for a second tank. In a single tank system, both hot and cold HTF are stored in the same tank since

Table 8
Different storage media used in concentrated solar power plants [84].

Storage medium	Temperature		Average density [kg/m³]	Average heat conductivity [W/mK]	Average heat capacity [W/mK]	Volume specific heat capacity [kWh/m³]	Media costs per kg [$/kg]	Media costs per kWh$_t$ [$/kWh$_t$]
	Cold [°C]	Hot [°C]						
Solid media								
Sand-rock-mineral oil	200	300	1700	1.0	1.3	60	0.15	4.2
Reinforced concrete	200	400	2200	1.5	0.85	100	0.05	1.0
NaCl (solid)	200	500	2160	7.0	0.85	150	0.15	1.5
Cast iron	200	400	7200	37.0	0.56	160	1.00	32.0
Cast steel	200	700	7800	40	0.6	450	5.00	60.0
Silica fire bricks	200	700	1820	1.5	1.00	150	1.00	7.0
Magnesia fire bricks	200	1200	3000	5.0	1.15	600	2.00	6.0
Liquid media								
Mineral oil	200	300	770	0.12	2.6	55	0.3	4.2
Synthetic oil	250	350	900	0.11	2.3	57	3.00	43.0
Silicone oil	300	400	900	0.10	2.1	52	5.00	80.0
Nitrite salts	250	450	1825	0.57	1.5	152	1.00	12.0
Nitrate salts	265	565	1870	0.52	1.6	250	0.70	5.2
Carbonate salts	450	850	2100	2.0	1.8	430	2.40	11.0
Liquid sodium	270	530	850	71.0	1.3	80	2.00	21.0
Phase change materials								
$NaNo_3$	308		2257	0.5	200	125	0.20	3.6
KNo_3	333		2110	0.5	267	156	0.3	4.1
KOH	380		2044	0.5	150	85	1.00	24.0
Salt-ceramics	500–850		2600	5.0	420	300	2.00	17.0
NaCl	802		2160	5.0	520	280	0.15	1.2
Na_2CO_3	854		2533	2.0	276	194	0.2	2.6
K_2CO_3	897		2290	2.0	236	150	0.6	9.1

they take the advantage of stratification. An example of such a tank is solar pond [61].

B.6.2. Passive systems

These systems are also called regenerators. The storage medium can be a solid [87], liquid, or PCM [88,89]. There is also possibility of high energy density storage in metal hydrides, where two media are required [90].

B.7. Solar chemistry

There is a need to store solar energy and transport it from the sunny uninhabited regions to the industrialized populated regions where it is needed. The way to achieve this is by thermochemical conversion of solar energy into chemical fuels. This method provides a thermo chemically efficient path for storage and transportation [91]. In order to drive endothermic reactions within high temperature processes energy is supplied by concentrating solar radiation. Applications include the solar reforming of low hydrocarbon fuels, solar gasification of biomass, production of solar aluminum, solar zinc and syngas, an ammonia synthesis reactor [92] and solar driven ammonia based thermochemical energy storage system [93].

B.8. Other

B.8.1. Swimming pools

Solar energy can be absorbed directly by the pool or indirectly by implemented solar collectors although there are also examples with solar ponds [94]. In this case solar pond itself serves as storage. The most common way to store energy is in a swimming pool. Proposed were also solutions with PCMs where they were either encapsulated in the sidewalls and bottom of the pool or used in an external heat exchanger [28].

B.8.2. Solar cooking

One of the problems of many solar cookers is the thermal storage where cooking during cloudy periods and late afternoons is not possible. With the storage unit this problem is avoided and cooker's temperature does not drop too much when cold food is added. Usually heat is stored in rocks, bricks, oil or PCM, such as magnesium nitrate hexahydrate [95], erythritol [96], lithium nitrate [97] and quicklime [98]. Classification of solar TES applications is presented in Fig. 9.

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